Is Climate Change a Factor in Observed Interdecadal Change in the Deep Puget Sound Benthos?

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Abstract
The benthos of central Puget Sound was quantitatively sampled twice yearly in most years between 1963 and 1992 to examine the concept of long-term stability in a deep- water (200m) community. The study showed that the most abundant species were consistently present over the 30-year period. However, measures of overall species composition and abundance reveal gradual change in the community. Among the changes are:
(1) aperiodic, multi-year bursts in the abundance of the common species, (2) an overall increase in the total abundance of the benthic community beginning in the mid-1970s; (3) periods of increased abundance, during the late 1970s and early 1980s, of two species that are tolerant of organic enrichment; and (4) the surprisingly steady decline in abundance of the large burrowing echinoderm, *Brisaster latifrons*. Despite the conspicuousness of these changes, there are no obvious environmental factors that readily explain them. Circumstantial evidence suggests changes in climate, organic enrichment, and predator abundance as possible influences. The principal reasons for our inability to identify causes of long-term change in the Puget Sound benthos are (a) presumed natural biological variability, and (b) inconsistent long-term monitoring of environmental variables. The study results highlight the need for consistent long-term monitoring data that can be used to evaluate changes in key biological populations and biologically relevant environmental variables that are expected to be influenced by human-induced stressors or remediation of those stressors.

Introduction
As described in the 1988 Puget Sound Research Conference proceedings (Nichols 1988), the benthos of central Puget Sound has been quantitatively studied since the early 1960s, beginning with the benthic community studies of Dr. Ulf Lie (e.g., Lie 1968). A subsequent year-long study of the benthos at five sites in central and southern Puget Sound (1969 through 1970) focused on the seasonal features of population biology and growth production of an important member of the benthic community, the polychaete worm *Pectinaria californiensis* (Nichols 1975). The latter study raised an obvious question: are observations made regarding benthic community composition in short-term studies (lasting no more than a year or two) relevant over a longer time span?

Two years after the completion of the initial study, sampling was repeated in spring of 1973, only to reveal that the numerically dominant species at the end of the 1960s had been essentially replaced by another species. Even in the deep and presumably stable environment of central Puget Sound, change was occurring. Sampling was conducted twice yearly over the next two decades to track long-term changes in the deep Puget Sound benthic community. The details of this long-term study will be published elsewhere. In this report the major changes are summarized, and conclusions are drawn about our ability to understand these changes.

Of the five sites studied in 1969-70, the three located close to Seattle-station FHN1 at 35-m depth in Port Madison; station FHN2 at 200-m depth in mid-Sound; and station FHN3 at 250-m depth off Alki Point (Figure 1)—were sampled until spring of 1992. The present analysis focuses primarily on the results from station 2 where Dr. Ulf Lie first collected quantitative benthos samples in 1963. Sample collection and handling have been described earlier (Nichols 1975 and 1988). More recently, the site has been sampled by the Washington State Department of Ecology (station MSMP29; e.g.; Llansó 1998) and the King County Department of Natural Resources (station KSJJ01; e.g., King County DNR 1998), extending the data further into the 1990s.

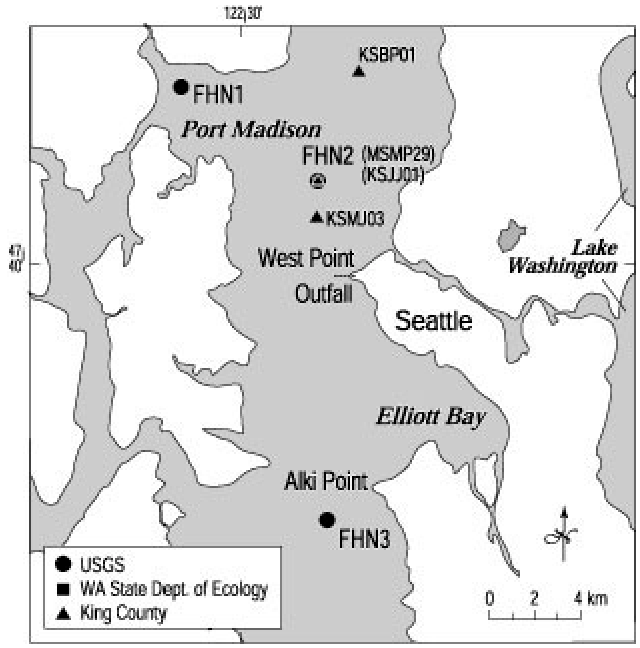

Figure 1 Central Puget Sound, with sampling locations: author's macroinvertebrate sampling stations FHN1-3; King County Marine Water Quality Program stations KSJJ01, KSMJ03, and KSBP01; Washington State Department of Ecology macroinvertebrate sampling station MSMP29.

The only environmental data available near the study site are routine water quality measurements made by King County on a frequent basis since the mid 1960s at two nearby sites sites (Figure 1, stations KSMJ03 and KSBP01). These data were examined for the purpose of reconstructing a time-series of water quality information. Unfortunately, while these water quality data have been very helpful in providing a context for studying ecological change over the multi-decadal period covered by this study, changes in the sampling program over time have prevented a quantitative analysis of environmental change.

Results

As reported in Nichols 1988, eight species were predominant members of the community at station 2. Six of the species are small but numerically abundant species that contributed a long-term average of roughly 75% of the total number of individuals in the community of more than 175 species: the polychaetes *Ampharete acutifrons* and *Pectinaria californiensis*, the clams *Axinopsida serricata* and *Macoma carlottensis*, and the crustaceans *Eudora pacifica* and *Euphilomedes producta*. The other two prominent species are two large, but routinely occurring species: the heart urchin *Brisaster latifrons* and the sea cucumber *Molpadia intermedia*. At the outset of the study, *Pectinaria* was the most abundant invertebrate at all of the sites sampled. By May of 1973, however, it was less abundant and became even less so during the next few years. It became prominent again in the mid-1980s (Figure 2).

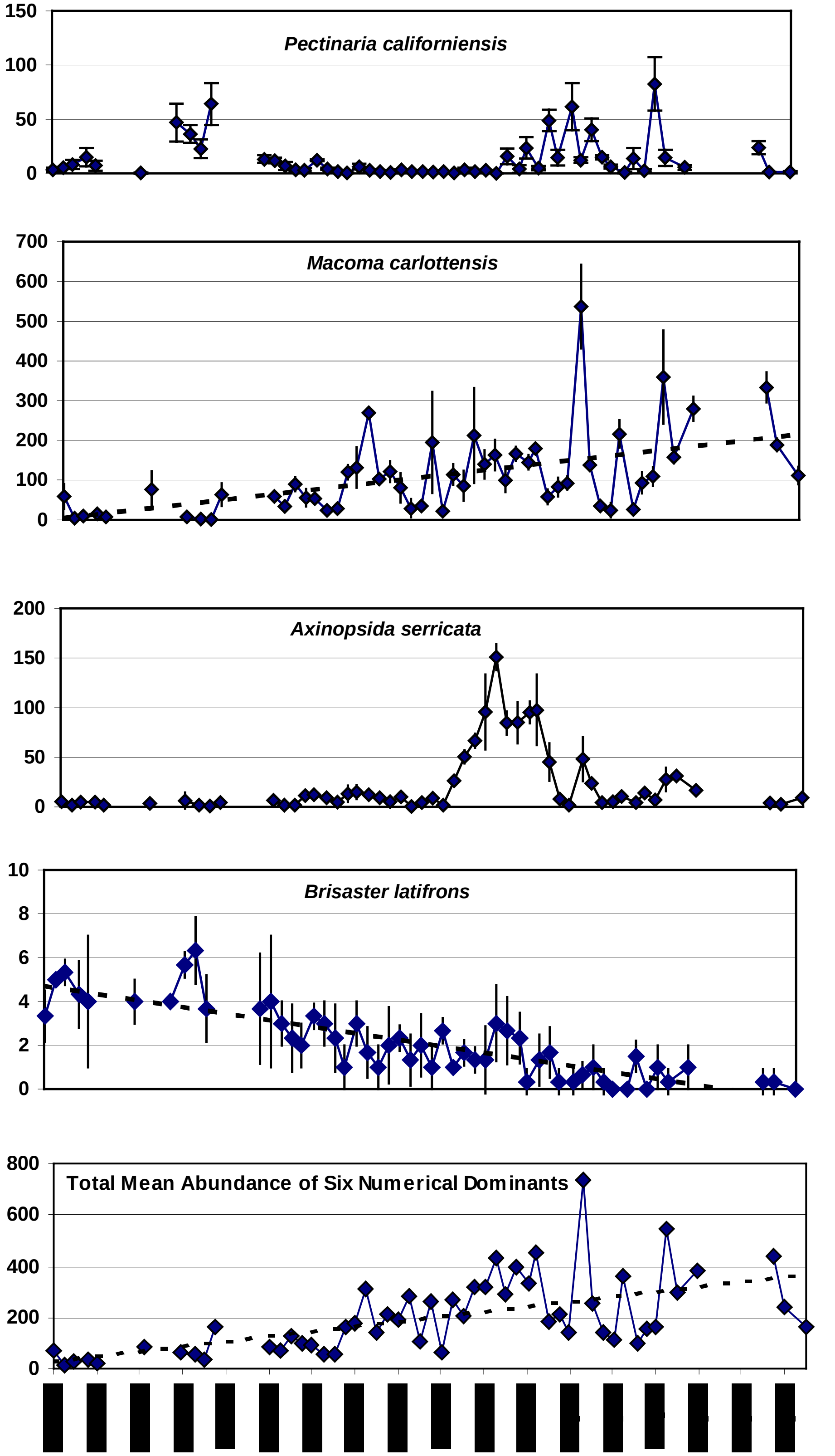

Figure 2 Abundances (± 1 s.d.) of three of the numerically dominant species and the heart urchin, as well as total mean abundance of the six numerically dominant species (the three species shown plus *Ampharete acutifrons, Euphilomedes producta,* and *Eudorella pacifica*). Data from 1993, 1997, and 1998 provided by WA Department of Ecology; data from 1996 provided by King County Department of Natural Resources. Dashed lines represent linear regression trend lines.

In contrast, a bivalve that was rare during the 1969 to 1970 sampling period, *Macoma carlottensis*, increased in abundance over the study period and, since the mid-1970s, has become the overwhelmingly dominant species in terms of abundance, with numbers routinely exceeding 200/0.1m2 (Figure 2).

The bivalve *Axinopsida serricata* (Figure 2) and the polychaete *Ampharete acutifrons* exhibited bursts of abundance during single prolonged periods in the late 1970s or early 1980s. Interestingly, these two species are commonly found in high abundance in organically enriched environments in Puget Sound and elsewhere.

The most pronounced change in the community during the more than 30 years of observations is the steady decline in the abundance of the largest animal in the community, the heart urchin *Brisaster latifrons*, that remains unexplained (Figure 2).

Overall, total abundance in the community, as expressed here by the sums of the abundances of the six numerically dominant species, has increased significantly over the duration of the study (Figure 2). Only continued sampling can reveal whether the upward trend will persist, although the more recent data collected by the Washington Department of Ecology and King County Department of Natural Resources may suggest otherwise, at least temporarily (Figure 2).

Agents of Change

What are the possible factors that might be contributing to the observed long-term changes in the community? We know that the human population in the King County area has grown, with the attendant increases in waste discharge, urban runoff, and other human influences on Puget Sound waters. We also know that in the mid-1960s, the sewage stream in King County was consolidated, in part to divert waste away from Lake Washington and the Seattle shoreline. A large portion of this waste stream, after primary treatment, was discharged at West Point through a pipe located about 4 km south of station 2, the primary study site (Figure 1). The assumption at the time of construction was that, because of the great size and depth of Puget Sound and its strong mixing properties, the effects of this consolidated waste stream would be non-consequential.

The data collected by the King County Marine Water Quality Program since the West Point Sewage Treatment Plant became operational are potentially useful for evaluating this hypothesis. However, because the field sampling program was periodically modified, i.e., changes over time in sampling location, depths, timing, frequency, and methodology, and did not include consistent measurement of potential water quality productivity (e.g., chlorophyll), the water quality data base does not facilitate analysis of biological trends.

As an example, secchi depth data taken at three of the King County stations closest to station 2 provide a hint that the surface waters of central Sound were more turbid during the 1980s. However, the changes in sampling frequency over time, with much less frequent sampling during the period in question, eliminate the possibility of a statistically valid assessment. One is left to speculate about whether there was indeed increased productivity in central Puget Sound during the 1970s and 1980s potentially stimulated by higher levels of organic materials and plant nutrients. If we assume that the organic matter in the waste stream entering the Sound translated into increased organic productivity and enhanced deposition of organic particles on the bottom, the small surface feeding benthos might have benefited through increased abundance, as has been observed. However, any organic enrichment of central Puget Sound waters was not of sufficient magnitude to affect bottom water oxygen concentration other than in several coves, inlets and channels where circulation is restricted. The King County oxygen data from deep Puget Sound bottom water show a strong seasonal signal but no measurable change over the long term. Undoubtedly because bottom waters of central Puget Sound are well mixed, there has been no sustained incidence of reduced oxygen concentrations like that plaguing many other urbanized estuarine and coastal systems around the world.

Declines in the catch rate of some Puget Sound bottomfish species reported by Palsson and others (1997), particularly the English Sole that is a major predator on the common benthic species found in this study, could have contributed to observed increases in benthic invertebrate abundance through decreased predatory pressure. But, whether the decline in English Sole catch rate since 1970 represents a true decline in the abundance of this species at the study site and, potentially, a reduction in predation on the small invertebrates there, is not known.

Climate Influence?

The King County water quality data have been useful in evaluating climatic influences on Puget Sound waters, particularly in documenting interdecadal changes in water temperature. Using the King County and other physical and biological data sources, Ebbesmeyer and colleagues (1991) showed that step-like changes in 40 time series of environmental variables from the Pacific coast and the Americas in 1976 through 1977 were remarkably consistent with a major climate change. This is now recognized as the Pacific Decadal Oscillation (PDO, e.g., Hare and Mantua 2000). One aspect of the climate shift of 1976 through 1977 was a decrease in precipitation and runoff into the Puget Sound basin that resulted in altered circulation and mixing within Puget Sound waters. These changes had the effect of changing the predominant southward flow of water from Admiralty Inlet from mid depth before 1977 to near the bottom after 1977. Could such an altered flow regime affect benthic invertebrates? Perhaps the increased invertebrate abundance seen at station 2, particularly noticeable after the mid-1970s, is in part a response to changes in the origin of near bottom water.

If climate is having an effect on the biota of the Sound, it should be seen as a broad-scale influence, not a local one. Interestingly, the major periods of increased abundances of the common species at station 2 were mirrored in time by abundance increases at the other two long-term sampling sites (Figure 1, FHN1 and FHN3) despite the distances between the sites and their quite different depths. The fact that major aperiodic changes in abundances of the common species are occurring at multiple sites in central Puget Sound suggests that biotic and abiotic processes operating on a broad geographic scale are influencing the distribution of benthic invertebrates, e.g., affecting the dispersal and/or survival of invertebrate larvae. Unfortunately, no long-term monitoring of plankton exists that would permit examination of hypotheses regarding the possible influence of climate-induced changes in Puget Sound circulation on pelagic larval dispersal.

If a goal is to evaluate change in Puget Sound in the context of both natural and human influences, and particularly to measure the effect of restoration actions, it will be necessary maintain a consistent, comprehensive long-term monitoring program designed to detect variations and trends in representative biotic and abiotic variables, including the normal water quality parameters as well as indicators of the plankton and fish communities. One time or annual monitoring information is only valuable when placed in this longer-term context. Without such a program, we can only continue to speculate about environmental change in Puget Sound.

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